Shape Memory Actuators for Tab-Assisted Control Surfaces

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1 Introduction

Shape memory alloy (SMA) actuators provide a variety of solutions to engineering problems which require actuators that can deliver high forces, high strokes, high energy densities, and, most significant for this research, high force-to-volume (or weight) ratios. Recent studies have shown the suitability of SMA actuators to aerodynamic problems that require large torque from actuators that must be housed within an airfoil's cross-section [2-3]. The extension of that research to tab-assisted control (TAC) surfaces is natural, and Lockheed Martin Astronautics (LMA) has developed one design. This report addresses the research challenges of using these actuators for TAC control and the challenges and roadblocks in forming a conclusion about the feasibility of using SMA for tab-assisted control.

2 Executive Summary

Actuation equations for a tab control system have been derived based on one-dimensional shape memory behavior. This actuation model accounts for the active tendon having to pull against the relaxing tendon in a two-tendon actuator. That is, the passive tendon will provide a negative moment, subtracting from the total moment available for moving the tab. In addition, studies on the heat convection of SMA in water and moving water have been performed in an attempt to determine the available control moment in moving water and to predict the amount of energy needed. These results identify the research issues

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13. ABSTRACT (Maximum 200 words)

Actuation equations for a tab control system have been derived based on one-dimensional shape memory behavior. This actuation model accounts for the active tendon having to pull against the relaxing tendon in a two-tendon actuator. That is, the passive tendon will provide a negative moment, subtracting from the total moment available for moving the tab. In addition, studies on the heat convection of SMA in water and moving water have been performed in an attempt to determine the available control moment in moving water and to predict the amount of energy needed. These results identify the research issues that must be overcome in making a recommendation regarding the feasibility of using SMA in a submarine for actuation. The result is that use of SMA is feasible, but the exact performance results are not predictable with the current state-of-the-art in SMA modeling. Furthermore, predictive design models specific to applications in moving water are needed to understand the issues of: 1) exact moment prediction, 2) exact heat signature and 3) control predictions for maneuvering.

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3 Background on SMA

Through proper heat treatment and processing, a shape memory alloy 'memorizes' a configuration. After large plastic deformation, greater than 1% strain, the alloy will return to its memory shape upon heating above a characteristic transition temperature. This memory effect is a result of a phase transformation from a low-modulus martensitic phase, at low temperatures, to a high-modulus austentic phase, at high temperatures. The change in modulus can be as much as a factor of 2.4 (e.g., from 35 GPa to 83 GPa).

There are several possible designs suitable for TAC. *Torque tubes* and *torque rods* are two possible design approaches for SMA. If these actuators are twisted, resulting in 'plastic' deformation, then upon heating the deformation is recovered due to the memory effect of the material [1]. Torque tubes have been used in a variety of aerodynamic applications to effect the twist of lifting and control surfaces [2,3,4]. Torque rods are a recent development and are attractive because they can be designed to exhibit two-way memory. This section describes some of the issues and specifics of these SMA actuators.

Torque tubes are constructed from thin-walled alloy stock; this ensures plastic deformation of all of the material. These actuators exhibit one-way memory and are used in a push-pull configuration. In this configuration, as the heated actuator cools, the cold actuator supplies a necessary bias stiffness, restoring the active element to its initial position.

Torque rods, however, can be designed for two-way memory. If properly designed, the central section remains elastic and acts a bias stiffness for the actuator [1]. The size of this elastic region and, hence, the bias stiffness, is dependent upon the applied load. As a torque rod actuator begins recovery upon heating, it cannot fully recover because of the internal bias. Because the center section has stored some potential energy, the stored energy will be released upon cooling and the actuator will rotate back to its initial position. Here, we focus on one-way memory effects.

4 Results and Technical Challenges

The results of previous work and the analysis provided under this program are presented next. Very limited experimental work using SMA's in a flowing water environment exists. The two most noteworthy efforts are, of course, the TAC work at NSWCCD [6] and the efforts of Lagoudas at Texas A&M [7], also funded by the Navy (under the STTR program, N0014-98-C-0061, monitored by Dr. Teresa McMullen). Our analysis is motivated by these efforts, plus the monthly reports submitted by NSWCCD and the open literature on SMA actuation.

Lockheed Test Results: From tests performed at NSWCCD and LMA on the LMA device, we learned that the TAC actuator consumed 20 watts in air and 400 watts in stirred water at 20°C. TAC produced about 25 lbs over 60° of motion. These values are for bare SMA wire immersed in water. A related experiment (Smart Vortex Leveraging Tab) had SMA embedded in silicone face sheets and produced about 1500 lbs. over 4 inches of tip displacement. Power consumption was about 3000 watts. These results imply that insulating to reduce power can reduce some of the energy wasted in heating the seawater; but, then you have to transport the heat out to reset the surface to neutral. This summarizes the main difficulty facing the use of SMA in flowing water applications.

Virginia Tech Analysis Results: In order to answer critical questions regarding the feasibility of using SMA as an actuator in a sea environment, a good, predictive design model is needed. A model of a push-pull SMA-based actuator was developed, and that model is described here. The model is followed by a discussion of the effects of heat transfer with the seawater, which forms the critical issue in the design of the TAC system. The basic conclusion is that some sort of insulation must be designed in order to work effectively within power restrictions for submarine applications.

Modeling: Here we examine a model using two shape memory wires connected to a tab of radius *R*, as indicated in Figure 1. Each wire is considered to operate using the one-way memory effect. At any given time, one wire is acting as a passive element (relaxing, or cooling) and one wire is acting in its heating or active state. It is important to note that this model best captures the critical features of actuation with SMA, as it clearly points out the forces involved in cooling or relaxing the actuator to its neutral state.

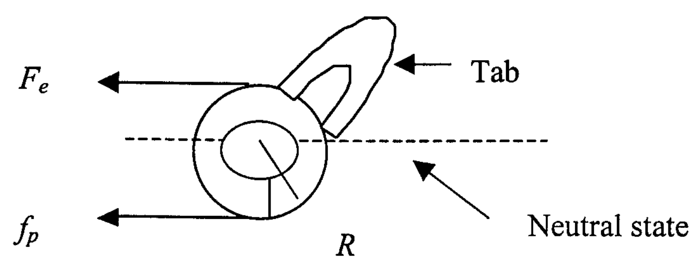

Figure 1 Geometry and forces of the tab actuator mechanics used in this study.

At low (room) temperatures and below (denoted M_f), SMA is in a crystalline state called Martensite with a specific, fairly high value of deflection. SMA's actuation behavior results from heating the material, usually through an applied current until it reaches a critical temperature, called the Austenite Start Temperature ($A_s > M_f$.) At this temperature, the microstructure of the SMA starts to change to a new crystal structure. This change of phase is completed if the temperature is increased to the Austenite Finish Temperature (A_f). The ability to change phase allows SMA to be mechanically loaded at one temperature, then reduced in temperature, storing a transformation stress that is negative. This stored stress constitutes memory and may be recovered by simply heating the SMA. This heating is usually accomplished by applying a current to the SMA.

The application of a current to induce heat in the SMA releases the stress resulting in a force in a relatively controlled way, with time history and magnitude determined by the applied current. However, returning to the relaxed state by cooling is not controlled and occurs according to the cooling environment surrounding the wire. In this application, the surrounding temperature is determined by flowing seawater, which has a strong effect on cooling (which is advantageous) as well as on heating (which is disadvantageous).

The goal of the actuator design is to generate a moment (with moment arm R) around the center point of the tab shown in Figure 1. Next we develop actuation equations, based on a simple one-dimensional SMA model. First consider the following notation: ε = strain, σ = stress, ℓ = wire length, f = tensile force, ℓ_r = undeformed wire length, and A_r = undeformed cross sectional area. Then the stress-strain relationships may be written as

$$\varepsilon = \frac{1}{2}\left[\left(\frac{\ell}{\ell_r}\right)^2 - 1\right], \qquad \sigma = \frac{f}{A_r}\left(\frac{\ell_r}{\ell}\right)$$

Solving for the force yields the relationship

$$f = \sqrt{1+2\varepsilon}\,\sigma A_r$$

Differentiating this last expression and evaluating the temperature dependence of the stress yields:

$$\frac{df}{dt} = F_\varepsilon \frac{d\varepsilon}{dt} + F_T \frac{dT}{dt} \tag{1}$$

where the coefficients have the following values:

$$F_\varepsilon = \frac{f}{1+2\varepsilon} + \pi_\varepsilon \sqrt{1+2\varepsilon}\,A_r, \qquad F_T = \pi_T \sqrt{1+2\varepsilon}\,A_r$$

Here the value of π_ε is dependent on the derivative of ε with respect to the martensite fraction and π_T is dependent on the variations of temperature, σ and ε with respect to temperature and martensite fraction.

Next let $\mathbf{q}$ be a vector of generalized coordinates describing the kinematic degrees of freedom of the wire. Then the time derivative of the strain becomes

$$\frac{d\varepsilon}{dt} = \left(\frac{\partial \varepsilon}{\partial \mathbf{q}}\right)^T \dot{\mathbf{q}} + F_T \frac{dT}{dt} \tag{2}$$

This last expression is the dynamic force relationship for an active SMA. This equation is coupled to the temperature-current relationship (Kreith and Bohn, 1986) given by

$$\tau \frac{dT}{dt} + (T - T_\infty) = cu, \quad u = I^2 \tag{3}$$

Here the value of τ and c are given by

$$\tau = \frac{\rho c_p A}{H d_s} = \frac{\text{(density)(specific heat capacity)(area)}}{\text{(Heat transfer coefficient)(circumference)}}$$

$$c = \frac{R_{el}\ell}{HA^2 d_s} = \frac{\text{(electrical resistance)(length)}}{\text{(Heat transfer coefficient)(area)}^2\text{(circumference)}}$$

Equations (2) and (3) form the dynamic equations governing the behavior of an SMA wire when activated by a current. With $u = 0$, these equations govern the behavior of an SMA wire as it cools off. The parameter τ is the thermal time constant and depends strongly on the value of the heat transfer coefficient H. The value of H on the other hand is extremely dependent upon the surrounding conditions. This dependency on the state surrounding the wire is the key design issue in the TAC design problem.

The key design parameter H, varies a great deal between still air, flowing air, water and flowing water. This is why the initial LMA design performed well in air but required much more power to perform in moving water. The value of H has theoretical changes as indicated (for horizontal cylinders, of 2.5-cm diameter):

H in free convection in still air: 6.5

H in free convection in still water: 890

H in forced convection in air flowing at 10 m/s: 65

H in force convection in water flowing at 0.5 m/s: 3500

Insulating sleeves can, of course, reduce H somewhat, as indicated by the LMA tests. Thus, the heat transfer of the SMA to moving water greatly reduces the effectiveness of the actuator or put another way, requires much more energy to activate the tab. The critical issue becomes one of determining whether or not the tab SMA drive can produce the required torque to meet the required specifications.

Next, a further important design parameter in estimating the amount of torque available to move the tab is explained. Examining a simple free-body diagram of the tab mechanism given in Figure 1 illustrates the second effect that reduces the available torque for controlling the tab. Taking the moment in Figure 1yields:

$$M = R(f_a - f_p)$$

where M is the moment available for moving the tab against hydrodynamic forces. Here f_a is the force provided by the activated SMA wire and f_p is the residual force in the passive SMA. Note that the passive SMA reduces the amount of moment available. This force satisfies equations (2) and (3) with $u = 0$. These equations are at the mercy of the value of H that is large in flowing seawater. In this case the seawater helps remove heat from the SMA and decreases the force f_p resulting in faster response and more moment.

However in order to make f_a large, the wire must be thermally insulated from the effects of seawater. Thus, we have two opposing design demands. On one hand, thermal insulation is needed to reduce the amount of current needed to move the tab, and on the other hand, we would like the seawater to be able to cool the relaxing SMA in order to maximize the available moment.

Alloy Selection There are perhaps eighteen types of alloys exhibiting the shape memory effect. However there are only three that are commercially available and, hence, dominate the available literature in SMA. These are Nickel-Titanium (Ni-Ti, also called Nitinol), Copper-Zinc-Aluminum (Cu-Zn-Al) and Copper-Aluminum-Nickel (Cu-Al-Ni). Nitinol has generally been favored in actuation applications because of its superior abilities compared to the other two. These are:

- Greater ductility
- Greater recoverable motion
- Corrosion resistance which is comparable to 300 series stainless steel
- Fairly stable transformation temperatures
- May be electrically heated for shape recovery.

The major drawback of Nitinol over the other two alloys is that it is a higher cost material. This is clearly overshadowed by its positive attributes. By comparison, Cu-Zn-Al has transformation temperatures that tend to drift during cycling. In addition, Cu-Zn-Al is prone to stress corrosion cracking depending on the operational environment. Cu-Al-Ni, on the other hand, is also less corrosion resistant than Nitinol and has the highest transition temperatures of the three alloys. As power is a major factor in these applications, the transition temperature should be lower than available with Cu-Al-Ni. Based on these considerations, Nitinol should be used.

It is important to note that because this material will be used in water (cold water), the insulation of these materials will also be an important consideration.

Hysteresis Considerations Temperature hysteresis occurs naturally in SMA-based systems. This means that the austenite-to-martensite transformation (forward reaction) occurs at a lower temperature range than the reverse transformation (martensite-to-austenite). The internal friction existing in the movement between the austenite and martensite interface mainly causes this effect. The main concerns in actuator design with hysteretic effects are the time delay introduced and the possibility that the actuator would not return to its original or set point. These effects must therefore be addressed by the mechanics of the situation and the control system used to actuate the tab. The transformation temperatures are greatly affected by external conditions such as the applied force, preloads and ambient temperatures. These factors - all present in this submarine application - make prediction of the hysteresis of the total system difficult from only analytical considerations. The question of how much hysteresis exists in a particular design can really only be answered by testing in situations similar to the actual application.

The actual values characterizing the hysteresis loop and its effects depend heavily on the austenite-to-martensite transformation temperatures. These, in turn, depend heavily on the relative rate at which heat is transformed away from the SMA. This is characterized by the heat transfer coefficient H. This key parameter varies several orders of magnitude when the external environment changes.

Torque, Power, Bandwidth and Time Constant: The key parameters in designing an effective actuator are torque, power, bandwidth and time constant. Each of these parameters will be different in various designs. The target values (6281 ft-lbs of torque, 30°of displacement, at a rate of 7°/s) again depend critically on the value of the illusive heat transfer coefficient. The heat transfer coefficient value is not given for any of the operating conditions in any of the data provided for this contract. In order to evaluate a given design analytically, this number is needed. Rather, we show the key parameters and equations governing the actuator performance.

The sensitivity of the required power to variations in the heat transfer coefficient H can be seen by examining equation (3), which can be written as

$$\frac{dT}{dt} + \frac{Hd_s}{\rho c_p A}(T - T_\infty) = \frac{R_{el}\ell}{\rho c_p A^3} I^2 \tag{4}$$

This equation admits an exponential solution with time constant determined by H for any fixed design (ρ, c_p, A and d_s are all fixed in each design). The value of H determines the rise time; bandwidth, time constant and the amount of current needed to control the temperature in the SMA. Combining equation (4) with equation (2) yields

$$\frac{d\varepsilon}{dt} = \left(\frac{\partial\varepsilon}{\partial \mathbf{q}}\right)^T \dot{\mathbf{q}} + F_T\left(\frac{Hd_s}{\rho c_p A}(T_\infty - T) + \frac{R_{el}\ell}{\rho c_p A^3} I^2\right) \tag{5}$$

Combining with equation (1) yields

$$\frac{df_a}{dt} = F_\varepsilon\left(\left(\frac{\partial\varepsilon}{\partial \mathbf{q}}\right)^T \dot{\mathbf{q}} + (F_T + \frac{F_T}{F_\varepsilon})\left(\frac{Hd_s}{\rho c_p A}(T_\infty - T) + \frac{R_{el}\ell}{\rho c_p A^3} I^2\right)\right) \tag{6}$$

Equations (4) and (6) imply the sensitivity of the dynamic force relationship for current in (I) to activate the SMA. Recall that T is temperature in the SMA needed to transform the SMA from austenite to martensite and that T_∞ is the temperature of the seawater.

The force f_a minus the spring force in the return element (or the force required to overcome the stiffness in the compliant mechanism design) is the force needed to produce the required torque. All of the relevant values for design (torque, bandwidth, power and time constant) in open-loop servo control depend on the solution of equations (4) and (6). Because H appears in the numerator of each of these equations, an order of magnitude change in H will overshadow any design choice. Many studies have verified that the coefficient H changes by two or more orders of magnitude between air and water and by four orders of magnitude in flowing water.

The time constant for the SMA actuator consists of two parts: one for cooling and one during heating. For cooling, it is shown in [7] that the fastest cooling is obtained when the current in the SMA is turned off. This could be enhanced by using the cool flowing seawater but it is not clear that the repeated use of flowing seawater (off when heating and on when cooling) is worth the extra design complexity. The current in the control wires may actually have to be stepped down rather than just shut off for relaxation (cooling) because of the large heat transfer coefficient in water. During heating or actuation of the SMA wire actuators, the time constant is determined by the amount of current applied, the load, the temperature at depth and the mechanical mechanism. This time constant must be matched to the submarine maneuvering demands. That is, the time constant must be fast enough to provide the position needed for the tab for the operational range of the submarine. This time constant cannot be determined without the specific load profiles to be experienced by the tab. However, the appropriate and key parameters can be identified from equations (1) through (6). Most of these parameters are not available from analytical or published numerical sources. Rather, the device must be constructed and tested to determine these values. Alternately, the equations derived here could be numerically simulated with a range of possible values of thermal constants. These simulations would then be useful in gaining some bounds on the performance of a given design based on estimated values of H. Hence, substantial design iteration is expected.

Interpretation: The LMA tests at NSWCCD produced a drastic reduction in performance due to the effect of being in moving water. The difference in wattage for the SMA being in water (240 watts, estimated) versus it being in air (10 watts) versus it being in water with 0.080-inch diameter silicone sleeves (80 watts) verify the above analysis in a qualitative way. One can compute times to actuation, given certain wire diameters and current capability. There is a nondimensional time constant factor introduced and for forced air versus still air, there is a difference of a factor of two for this time constant, the forced air case requiring longer time. From basic convective heat transfer, there is relationship for convective heat transfer, which involves the convective heat transfer coefficient (sometimes called the film conductance). Published values of the parameter for typical situations reveal again that forced airflow results in greater heat transfer by a factor of 2 or 3 relative to free air. However, for water flow, the convective heat transfer is greater by an order of magnitude, or more. The conclusion is that some of the difference in wattage requirements is due to water tunnel conditions versus air conditions used in the initial design. The added silicone sleeves have some effect in reducing the effect of heating up the water rather than moving the actuator. However, a thermally-insulating sleeve also causes the relaxation force to be larger, still reducing the available moment. In addition, some energy is lost to the mechanical motion of the sleeve, but this may not be too significant. This is an unknown quantity that needs further calculation.

To verify this further, consider experiments run at Texas A&M by Lagoudas' group [7]. These published results also verify the analysis provided above in a qualitative way. The experiments consisted of deflecting an SMA wire in water flowing at 0.415 m/s and comparing this to airflow at a similar rate. As predicted, the required current was higher in water flow than in airflow. In addition, the cooling cycle still requires significant current. Although power measurements were not recorded, a 0.2-inch deflection in a 0.415 m/s flow required 8 amps in air and 20 amps in water. In terms of deflection, the same current factor produced a 40% smaller deflection in water than it did in air. These findings are consistent with both the analysis provided above and with the conclusion, that the major impasse in constructing an SMA-based tab control are exactly the issues of heat transfer in the actuator.

5 Conclusion and Recommendations

In conclusion, the idea of using SMA to activate a tab for control has obvious merit. Initial designs failed to meet the desired specifications, but the design limits and principles have been identified to be the heat transfer between the actuator and the flowing seawater. Future designs need to account for the physics represented in equations (2) and (3) above. The design trade-off will consist of SMA wire sizing, and sleeve insulation, and geometry. Other designs are possible such as the camber changing mechanism suggested in [9] and alternate designs used at LMA.

Using an antagonistic actuation of a compliant control surface, as suggested in [6], may be the best mechanism from the point of view of the heat transfer problem. This would at least change the heat transfer coefficient (*H*) from 3500 to 890, thus reducing the amount of power required by a factor of four, or alternately, increasing the actuation efficiency by a factor of four.

It is recommended that equations (2) and (3) above be experimentally verified and the coefficients be determined experimentally. Once these coefficients are known experimentally, the equations can be used to predict the torque and power needed to actuate the tab for successful TAC. Lagoudas [7] has the appropriate experimental facility to obtain the physical parameters. Our conclusion is that models do not currently exist with enough accuracy to predict the available torque from any SMA-based design. Torque calculations, actuation speed, and all other design parameters depend critically on the value of the heat transfer coefficient. This value can only be determined experimentally. Furthermore, the effective heat transfer coefficient will be different for each design variant. Those torque, power, bandwidth and speed-of-response calculations presented in the literature and in various tab-related reports, based entirely on analysis, are all suspect and likely to be in error. The heat transfer coefficient effects all of the key design parameters, yet is not even included in the referenced material.

It is also recommended to test the compliant mechanism approach suggested in [6]. This approach may remove the negative effects of flowing seawater, as the skin of the compliant mechanism will separate the flow from the actual wires. This brings the value of the heat transfer coefficient back into a range more suitable for use with servo control and with smaller power requirements. The exact values of the coefficient again need to be determined experimentally. However, the above analysis does show that this approach would require less energy. However, more energy is needed for bending the compliant surface. This also depends on the detailed design. To determine the total required energy for this design, the forces due to the flow (estimated by NSWC to be that required for a moment of 6,281 ft-lb) need to be added to the forces required to overcome the stiffness of the compliant mechanism.

Preliminary test results indicate that the SMA TAC concept is feasible. It remains to develop predictive models and to use these to formulate successful designs based on the heat transfer coefficient, measured across the operating range of temperatures and relative flow rates. Alternately, numerical simulations could be employed, using the analysis developed here. These simulations could reduce the cost of repeated experiments in obtaining a final design.

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